Hypernuclear experiments at K1.1 in future

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1. **Gamma-ray spectroscopy of Λ hypernuclei at K1.1**

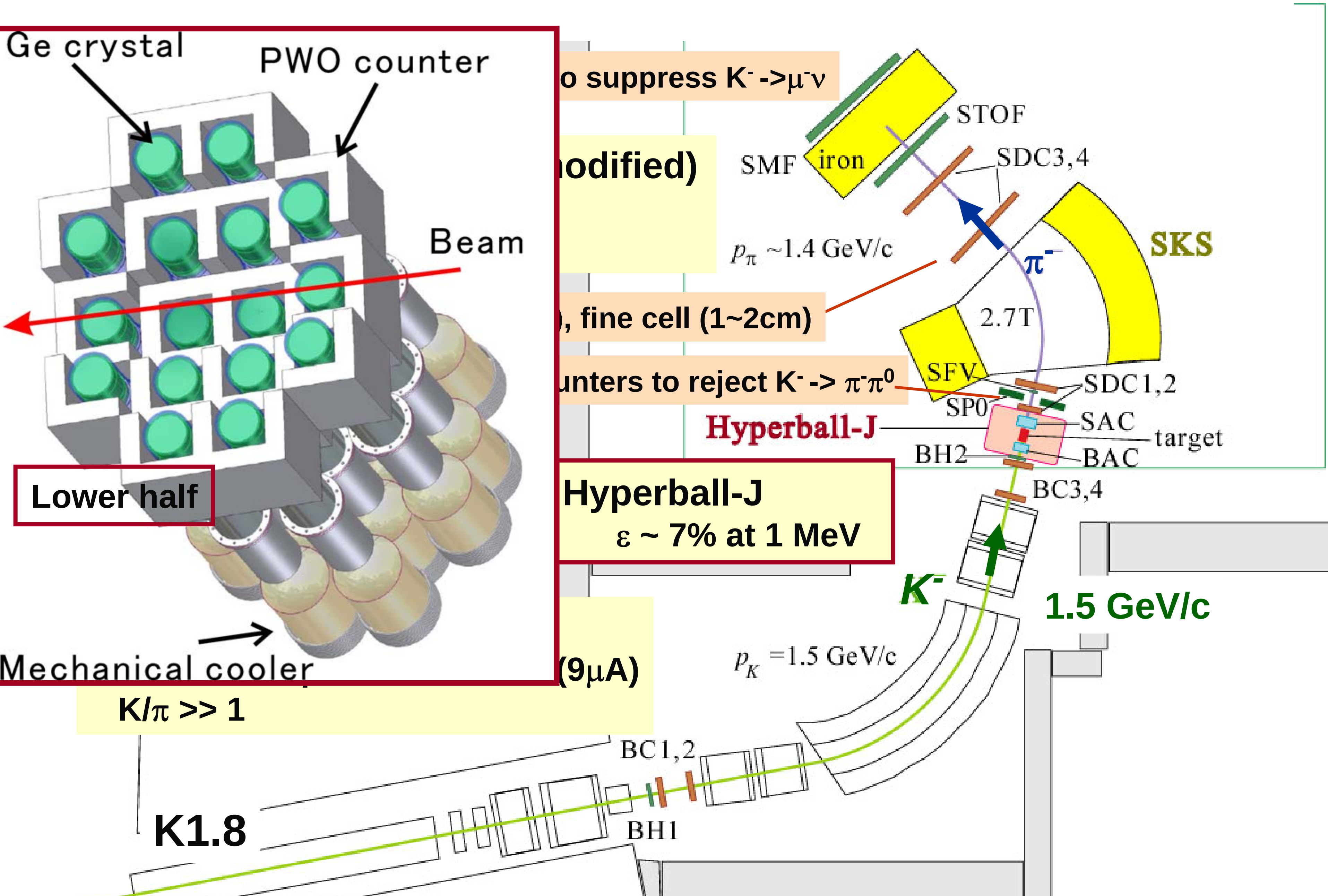
2. **Light Σ hypernuclei by (K^-,$\pi^{\pm,0}$) at K1.1**

3. **γ decay of Σ hypernuclei at K1.1**

Coulomb-assisted hybrid states -> HR pion line (Noumi-san)

1. Gamma-ray spectroscopy of Λ hypernuclei at K1.1

Beam and Setup for γ spectroscopy



LOI for γ spectroscopy (2003)

Reaction / p (GeV/c) ; Beamline ; Features

(1) *Complete study of light (A<30) hypernuclei* …, $^{20}_{\Lambda}$Ne, $^{23}_{\Lambda}$Na, $^{27}_{\Lambda}$Al / $^{28}_{\Lambda}$Si

(K^-,π^-) p= 1.1 and 0.8 ; K1.1 ; $\gamma\gamma$ coin, angular corr. , B(E2),..

"Table of Hyper-Isotopes" ΛN interaction (ΛN–ΣN, p-wave, ..) Shrinkage, collective motion, ...

Partly in E13

(2) *Systematic study of medium and heavy hypernuclei* $^{89}_{\Lambda}$Y, $^{139}_{\Lambda}$La, $^{208}_{\Lambda}$Pb

(K^-,π^-) p=0.8-1.8 ; K1.1 and K1.8 ; p-wave ΛN interaction

(3) *Hyperfragments* $^{8}_{\Lambda}$Li, $^{8}_{\Lambda}$Be, $^{9}_{\Lambda}$B,…

K^--in-beam (stopped K^-) p=0.8 ; K1.1 ; p/n-rich hypernuclei,

(4) *n-rich and mirror hypernuclei* $^{7}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{12}_{\Lambda}$B...

Shirotori's talk

(K^-,π^0) p= 1.1 and 0.8 ; K1.1 ; charge sym.break., shrinkage of n-halo,

(5) *B(M1) using Doppler shift* $^{7}_{\Lambda}$Li and heavier

Partly in E13

(K^-,π^-) p= 1.1 and (π^+,K^+) p= 1.05 ; K1.1 ; μ_Λ in nucleus

(6) *B(M1) using γ-weak coincidence*

(K^-,π^-) p= 1.1 and 0.8 ; K1.1 ; ρ, T dependence of μ_Λ in nucleus

S=-2

Reaction / p (GeV/c) ; Beamline ; Features

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(7) ***Ξ atom X rays***

E03, E07

(K^-, K^+) p=1.8 GeV/c; K1.8 ; ΞN interaction

(8) ***ΛΛ-hypernuclei***

(K^-, K^+) p=1.8 GeV/c; K1.8 ; ΛΛ, ΞN-ΛΛ interactions

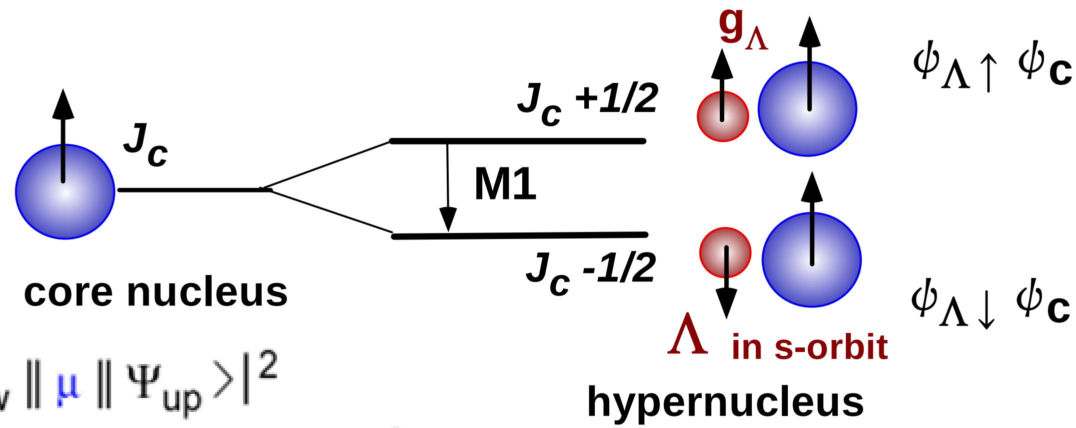
(5),(6) B(M1) measurements

μ_Λ in nucleus -> medium effect of baryons

Constituent quark

$$\mu_q = \frac{e\hbar}{2m_q c}$$

μ_q changes in nucleus?



$$B(M1) = (2J_{up}+1)^{-1}\,|\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$

$$= (2J_{up}+1)^{-1}\,|\langle \psi_{\Lambda\downarrow}\psi_c \| \mu \| \psi_{\Lambda\uparrow}\psi_c \rangle|^2$$

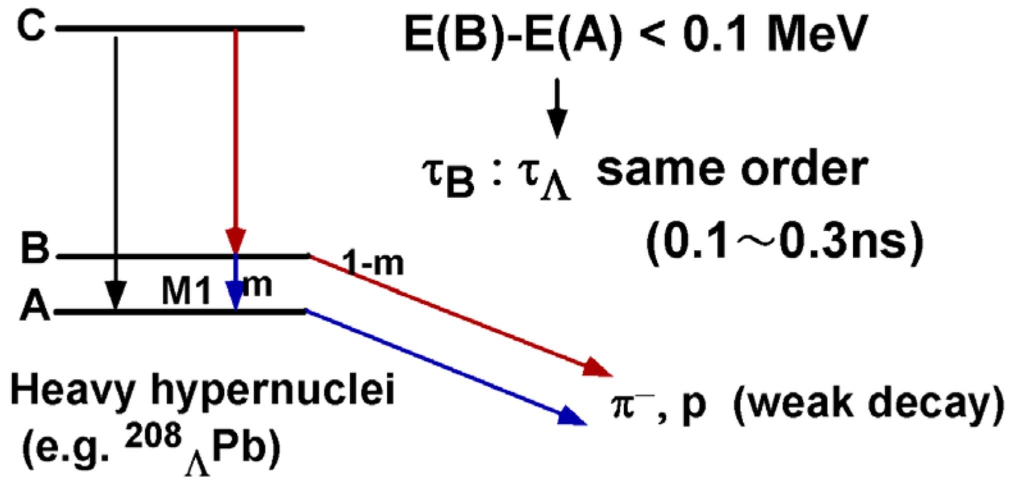
$$\mu = g_c \boldsymbol{J}_c + g_\Lambda \boldsymbol{J}_\Lambda = g_c \boldsymbol{J} + (g_\Lambda - g_c)\boldsymbol{J}_\Lambda$$

$$= \frac{3}{8\pi}\,\frac{2J_{low}+1}{2J_c+1}\,(g_\Lambda - g_c)^2 \quad [\mu_N^2]$$

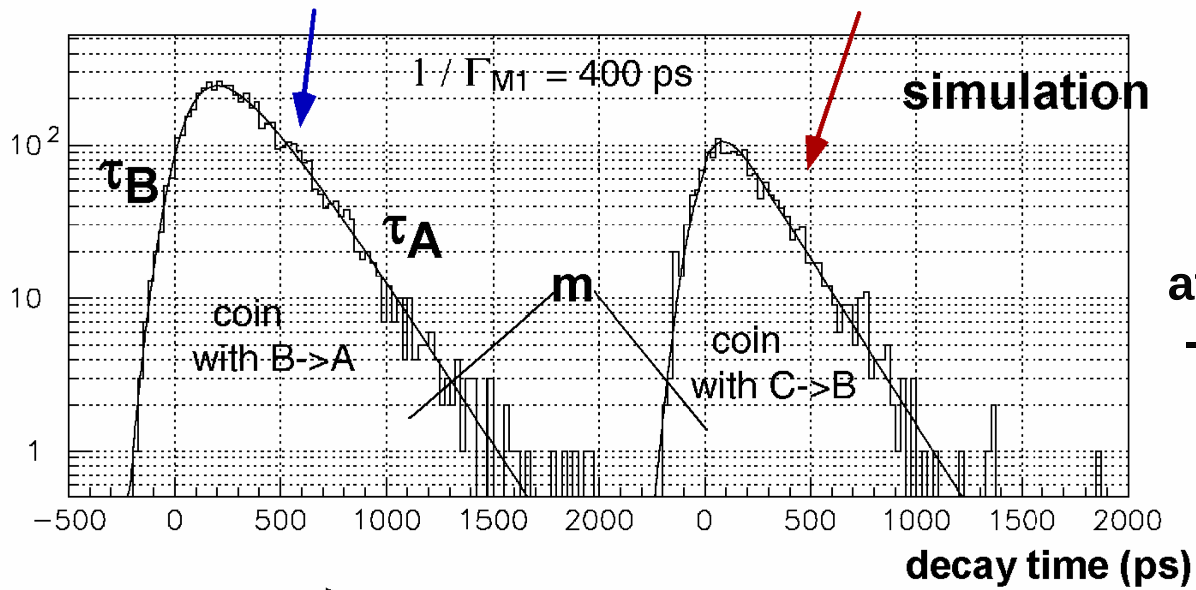
Partly in E13

- **Doppler shift attenuation method** *[same as B(E2), established]*
  for light hypernuclei; Weak K^- or π^+ beam usable
- **γ-weak coincidence method** *[new, only possible at J-PARC]*
  for $^{12}{}_\Lambda$C and heavy hypernuclei; Intense K^- beam necessary

B(M1) measurement by γ-weak coincidence method



Measure the time spectra of weak decay particles
in coincidence with B->A γ ray and with C->B γ ray



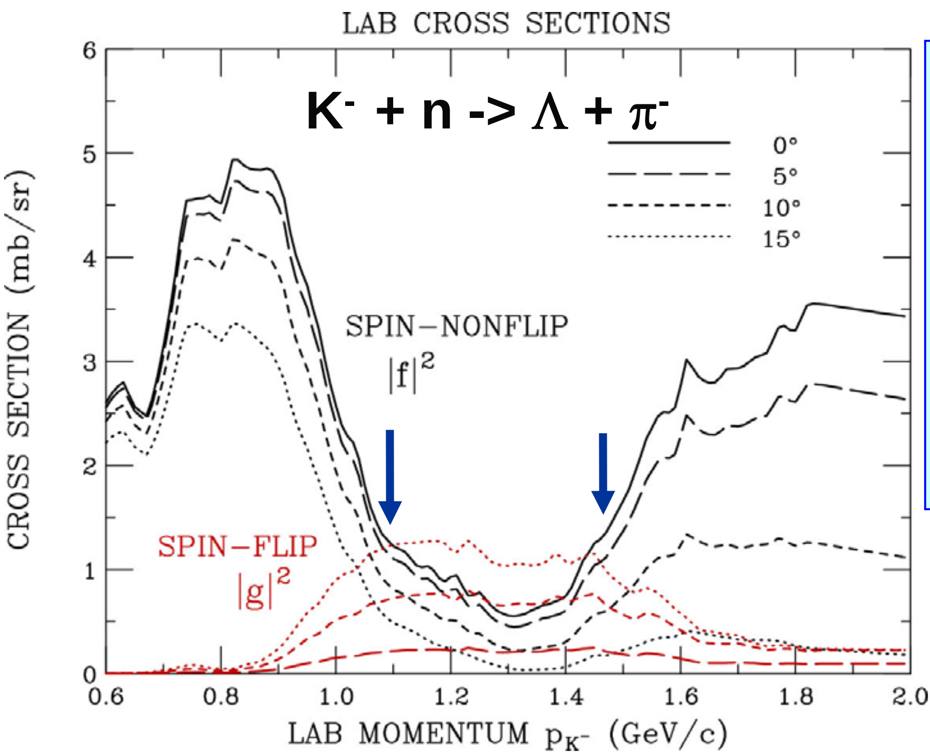
$^{12}{}_\Lambda$C case

900 hours, 9×10^6 K^-/spill
at K1.1 (50 GeV full beam)
-> 5% stat. error of B(M1)

-> m, τ_B

-> $m / \tau_B = \Gamma_{M1} \propto B(M1)$

Best K^- beam momentum



K1.1: More yield x4

Less Doppler shift

Need to move SKS to K1.1

(and construct "SKS2" at K1.8)

or construct another SKS

at K1.1

Ω= 20 msr (SPESII)

Ω= 100 msr (SKS)

Both spin-flip and nonflip states should be produced.

-> p_K = 1.1 or 1.5 GeV/c

p_K = 1.1 GeV/c : K1.1 + "SKS" (ideal)

p_K = 1.5 GeV/c : K1.8 + SKS (realistic)

N(1.1) = 2.0x10^6/spill at K1.1

N(1.5) = 0.5x10^6/spill at K1.8

(30 GeV 9μA)

High K/π ratio to minimize radiation damage to Ge detectors

-> Double-stage separation. K1.8BR is not good.

2. Light Σ hypernuclei by $(K^{-},\pi^{\pm,0})$ at K1.1

Quark DOF really necessary in BB interaction?

- ΛN spin-orbit force (Λ–spin-dependent LS force ~ 0)
  - -- $^{9}_{\Lambda}$Be, $^{13}_{\Lambda}$C γ-spectroscopy data
- Σ ...)
  - - ... uclear pot.
- S ...

	Δ	S_Λ	S_N	T (MeV)	
ND	-0.048	-0.131	-0.264	0.018	G-matrix calc. by Yamamoto
NF	0.072	-0.175	-0.266	0.033	
NSC89	1.052	-0.173	-0.292	0.036	
NSC97f	0.754	-0.140	-0.257	0.054	
("Quark"		0.0	-0.4	)	
Exp.	0.4	-0.01	-0.4	0.03	

"Quark": Strength equivalent to quark-model LS force by Fujiwara et al.

Σ hypernuclei and ΣN interaction

- $^{4}_{\Sigma}$He bound state -> T=1/2 attractive
  ^{4}He(K^-,π^+) -> T=3/2 repulsive

$\Rightarrow$ Lane term $(\sigma_\Sigma \sigma_N)(\tau_\Sigma \tau_N)$ consistent with Nijmegen interactions

- No bound-state peaks in $^{6}_{\Sigma}$Li, $^{7}_{\Sigma}$Li, $^{9}_{\Sigma}$Be, $^{12}_{\Sigma}$C
- Σ atomic data – attraction at outer nuclear region
  (not direct information)
- ^{28}Si,..(π^-,K^+) spectrum -> spin-averaged pot. strongly repulsive (~ +30 MeV)

=>Lane term $(\sigma_\Sigma \sigma_N)(\tau_\Sigma \tau_N)$ (by π/ρ.. exchange) consistent, but strength of each spin-isospin channel and $\Sigma N \to \Lambda N$ not determined yet.

T=3/2,S=3/2 channel strongly repulsive? (by quark Pauli)

=> More data for light (spin-isospin unsaturated) hypernuclei

G-matrix results for various interactions

Rijken et al., PRC59 (1999) 21

TABLE XIV. Contributions to U_Σ at $k_F = 1.0\ \mathrm{fm}^{-1}$ in the cases of NSC97e, NSC97f, NSC89, NHC-F, and NHC-D. Conversion widths Γ_Σ are also shown. All entries are in MeV.

	Isospin $T=\frac{1}{2}$			Isospin $T=\frac{3}{2}$				
Model	$^1S_0$	$^3S_1$	P	$^1S_0$	$^3S_1$	P	Sum	Γ_Σ
NSC97e	5.2	−7.5	0.0	−6.1	−2.5	−0.9	−11.8	14.6
NSC97f	5.2	−7.6	0.0	−6.2	−2.2	−0.9	−11.6	15.5
NSC89	3.0	−4.2	−0.3	−5.8	3.7	0.1	−3.6	25.0
NHC-F	4.2	−10.9	−1.5	−5.3	18.6	−1.7	3.5	16.3
NHC-D	2.1	−9.6	−2.2	−5.4	9.4	−3.0	−8.7	8.7
ESC04d	6.5	-21.0	-3.4	-20.2	24.0	-20.9	-26.0	
fss2(quark)	6.7	-23.9	-5.2	-9.2	41.2	-1.4	7.5	

Rijken, Yamamoto PRC73 (2006) 044008

Fujiwara et al., Prog.Part.Nucl.Phys. 58 (2007) 439

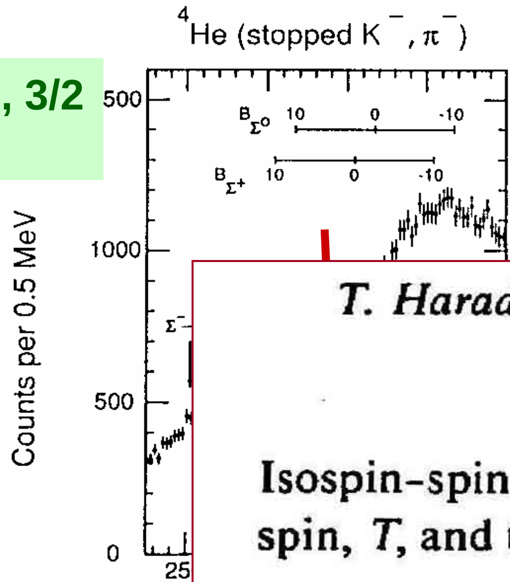
$k_f = 1.35\ \mathrm{fm}^{-1}$

Lane term $(\sigma_\Sigma\sigma_N)(\tau_\Sigma\tau_N)$ by π/ρ exchange

quark Pauli effect

$^{4}_{\Sigma}$He by (K^-,π)

T=1/2, 3/2
S=0



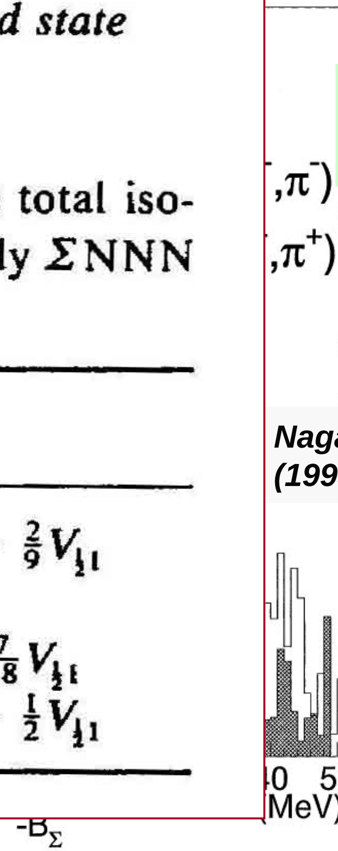
Substitutional (ΔL=0) state: $n(s_{1/2})^{-1}\Lambda(s_{1/2}1)$

T. Harada et al. / $^{4}_{\Sigma}$He hypernuclear bound state

TABLE 2

Isospin–spin averaged ΣN potentials for the total isospin, T, and total spin, S, state in the four-body ΣNNN system.

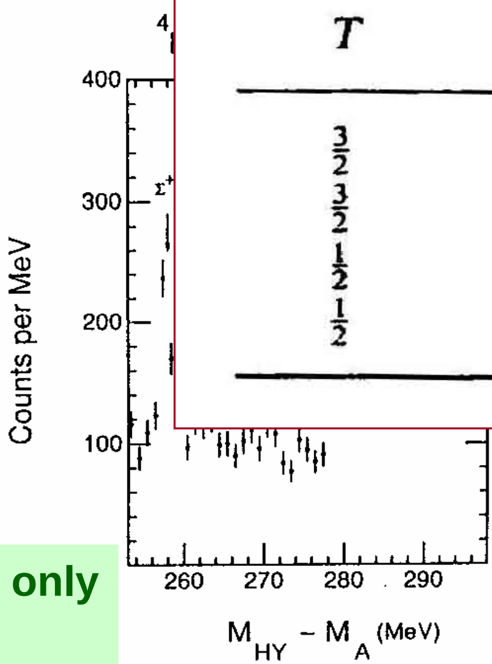
T	S	$\bar{V}_{\Sigma N}$
$\frac{3}{2}$	1	$\frac{1}{6}V_{\frac{3}{2}0}+\frac{11}{18}V_{\frac{3}{2}1}+\frac{2}{9}V_{\frac{1}{2}1}$
$\frac{3}{2}$	0	$\frac{5}{18}V_{\frac{3}{2}0}+\frac{1}{2}V_{\frac{3}{2}1}+\frac{2}{9}V_{\frac{1}{2}0}$
$\frac{1}{2}$	1	$\frac{4}{9}V_{\frac{3}{2}1}+\frac{1}{6}V_{\frac{1}{2}0}+\frac{7}{18}V_{\frac{1}{2}1}$
$\frac{1}{2}$	0	$\frac{4}{9}V_{\frac{3}{2}0}+\frac{1}{18}V_{\frac{1}{2}0}+\frac{1}{2}V_{\frac{1}{2}1}$



T=1/2, 3/2
S=0

T=3/2 only
S=0

Nagae et al., PRL 80 (1995) 1605



T=3/2 only
S=0

Large spin-isospin dependence (Lane term)

- Consistent with ΣN interaction in Nijmegen D model
  - (I,S) = (3/2,0), (1/2,1) attractive, (3/2,1), (1/2,0) repulsive

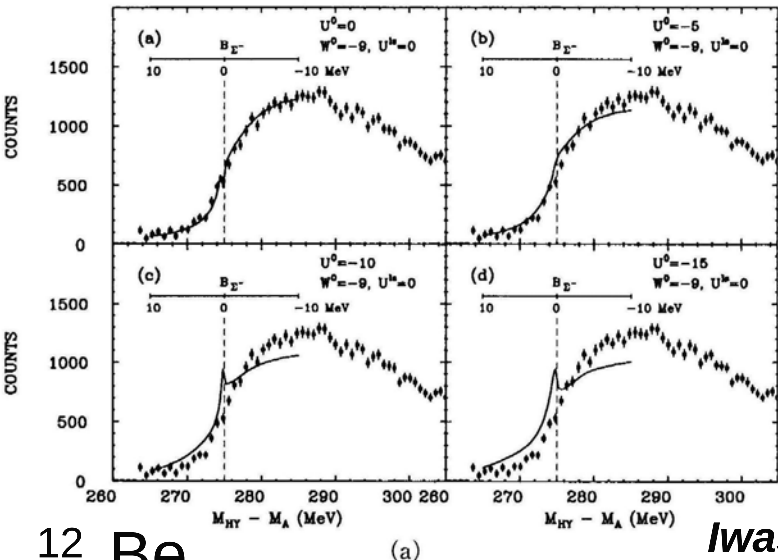
No peaks in other Σ hypernuclei

- Width ($\Sigma N \to \Lambda N$) > 10 MeV in general-- spectroscopy difficult

Other Σ hypernuclei?

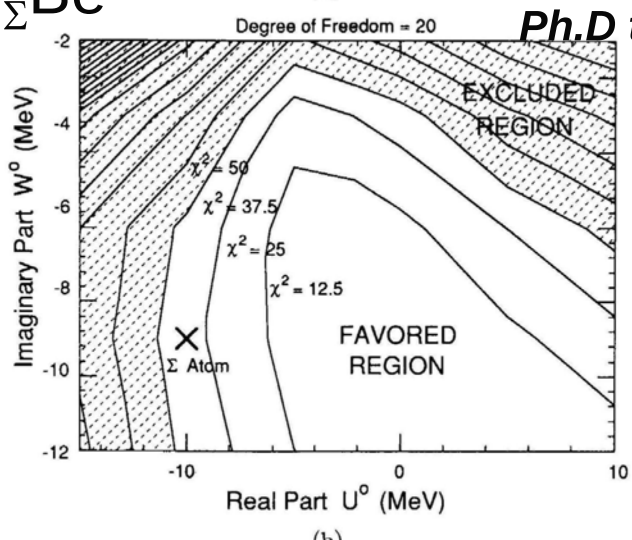
Bart et al. PRL 83 (1999) 5238

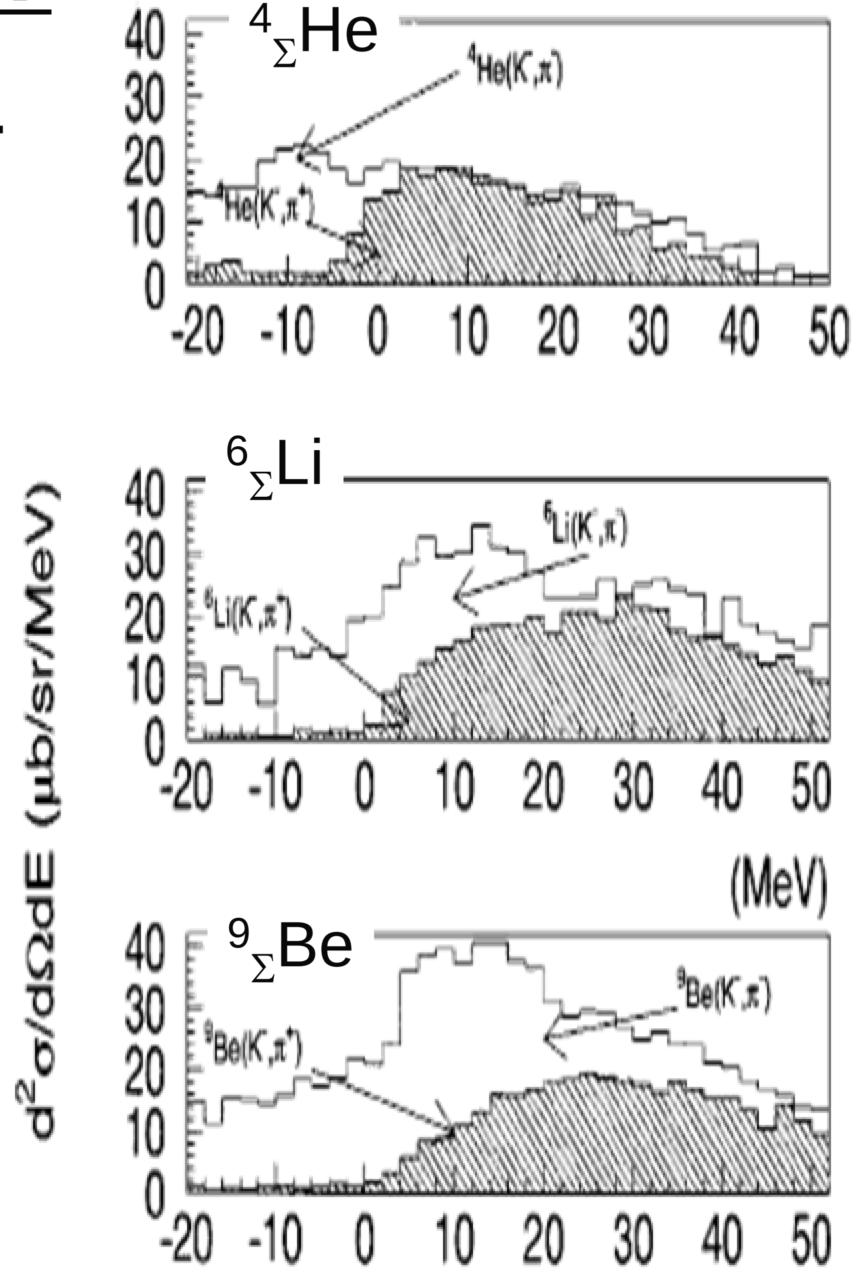
No Σ bound states in A>4



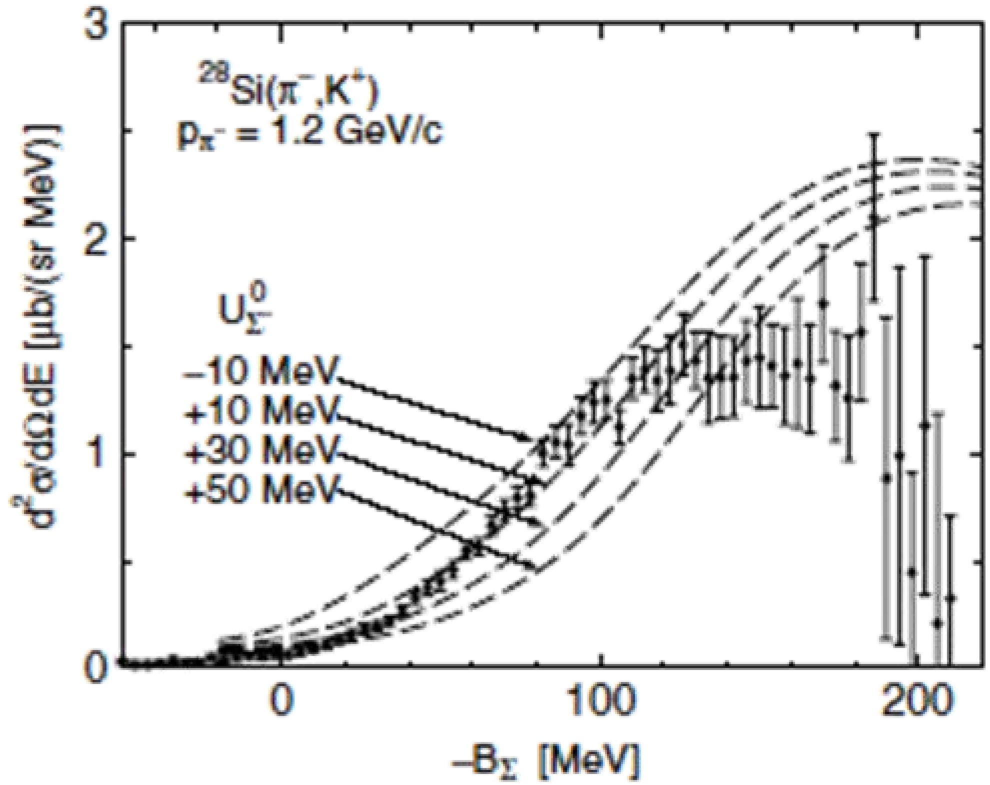
$^{12}_{\Sigma}$Be

Iwasaki Ph.D thesis (1987)





Repulsive potential?



U_Σ ~ +30 MeV

FIG. 9. $(\pi^-, K^+)\Sigma$ formation inclusive spectra with a ^{28}Si target at $\theta_K = 6° \mp 2°$ for pions with $p_\pi = 1.2$ GeV/c. These results were obtained with four choices of the strength $U^0_\Sigma = -10, 10, 30, 50$ in a Woods-Saxon potential form with the geometry parameters of $r_0 = 1.25 \times (A-1)^{1/3}$ fm and $a = 0.65$ fm. Experimental data points are taken from Refs. [22,23].

Data: Noumi et al., PRL 87 (2002) 072301
Calc: Kohno et al., PRC 74 (2006) 064613

Previous $^3He(K^-,\pi^-)$ data at BNL E774

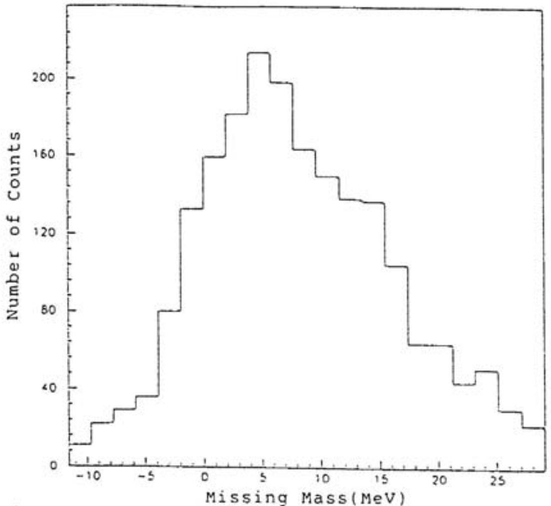


Fig. 1 Missing Mass Spectrum of $^3He(K^-,\pi^+)$ reaction.

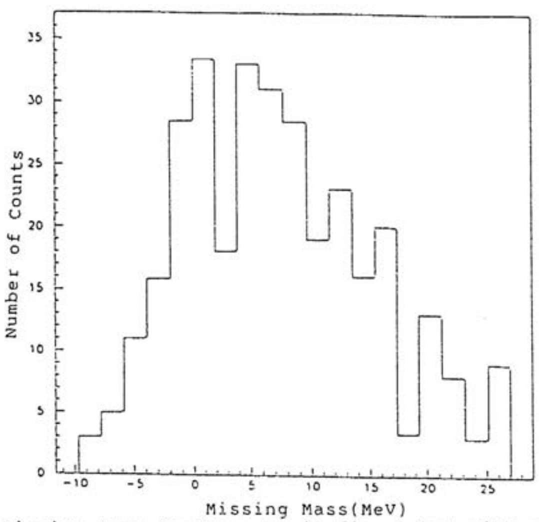
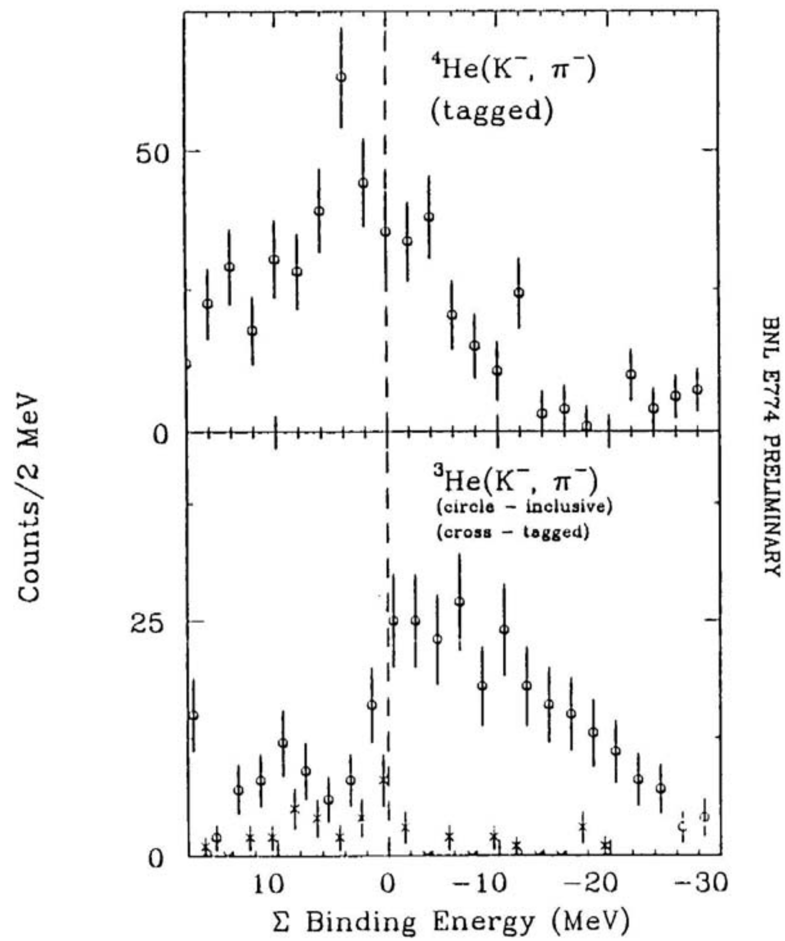


Fig. 2 Missing Mass Spectrum as in fig. 1 but with multiplicity 2 cut.

R.S. Hayano / ^4He $(K^-,\pi^\pm)$ experiments at KEK and BNL 155c



Top: $^4He(K^-,\pi^-)$ data tagged with the multiplicity ≥ 2 condition (same as ›m-left). Bottom: $^3He(K^-,\pi^-)$ spectra. Inclusive data are in open circles and multiplicity-tagged data are in crosses.

Proposed ^{3}He experiment

- ^{3}He (K^-,$\pi^{\pm,0}$ Λ) at threshold, p_K~0.5~0.6 GeV/c (q < 50 MeV/c)
- $^3_\Sigma$He, $^3_\Sigma$H, $^3_\Sigma$n : different combination of
  ($T_{N\Sigma}$,$S_{N\Sigma}$) = (3/2,1), (3/2,0), (1/2,1), (3/2,0) from $^4_\Sigma$He, $^4_\Sigma$n
- 3-body systems can be accurately calculated
  -> direct comparison with various interactions
  (how sensitive? – theoretical calculations essential)
- Apparatus: Low momentum beam line (K1.1BR)
  + beam spectrometer + SPESII and π^0 spectrometer + Λ tagger (CDS)

Koike-Harada (NPA611(1996)461) "Unstable bound states"

E_Σ (Γ)	SAP-1(ND)	SAP-F(NF)
$^3_\Sigma$He (T=1,S=1/2)	---	+1.77 (7.58) MeV
$^3_{\Sigma 0}$H (T~1,S=1/2)	+0.01 (1.95)	+0.63 (8.2) MeV
$^3_\Sigma$n (T=1,S=1/2)	---	+0.55 (9.05) MeV

Spectral shapes should be calculated.

Experiment

- Beam spectrometer (Δp_{FWHM} <1.5 MeV/c at 600 MeV/c)
  in place of K1.1BR B3
- 3He target
- Λ tagger => CDS
- $\pi^{\pm}$ spectrometer (Δp_{FWHM} <1.5 MeV/c at 500 MeV/c)
  => SPESII
- π^0 spectrometer (Δp_{FWHM} ~ 3 MeV/c at 500 MeV/c)

Yield (K^-, $\pi^{\pm}$): $N_{K-} \cdot d\sigma/d\Omega \cdot \Delta\Omega \cdot N_{target} \cdot \varepsilon(\Lambda tag) \cdot \varepsilon$

$= 5\times10^5$ /spill $\cdot 50\times10^{-30} cm^2/sr \cdot 0.02 sr \cdot 0.09 g/cm^3 / 3 \cdot 10 cm \cdot 6\times10^{23} \cdot 0.3 \cdot 0.5$

=> 1400 counts/100hours ***->Lower beam momentum?***

Yield (K^-, $\pi^{\pm 0}$):

=> ~100 counts/100hours

Λ *tagging is essential*

Data: Nagae et al., PRL 80 (1995) 1605

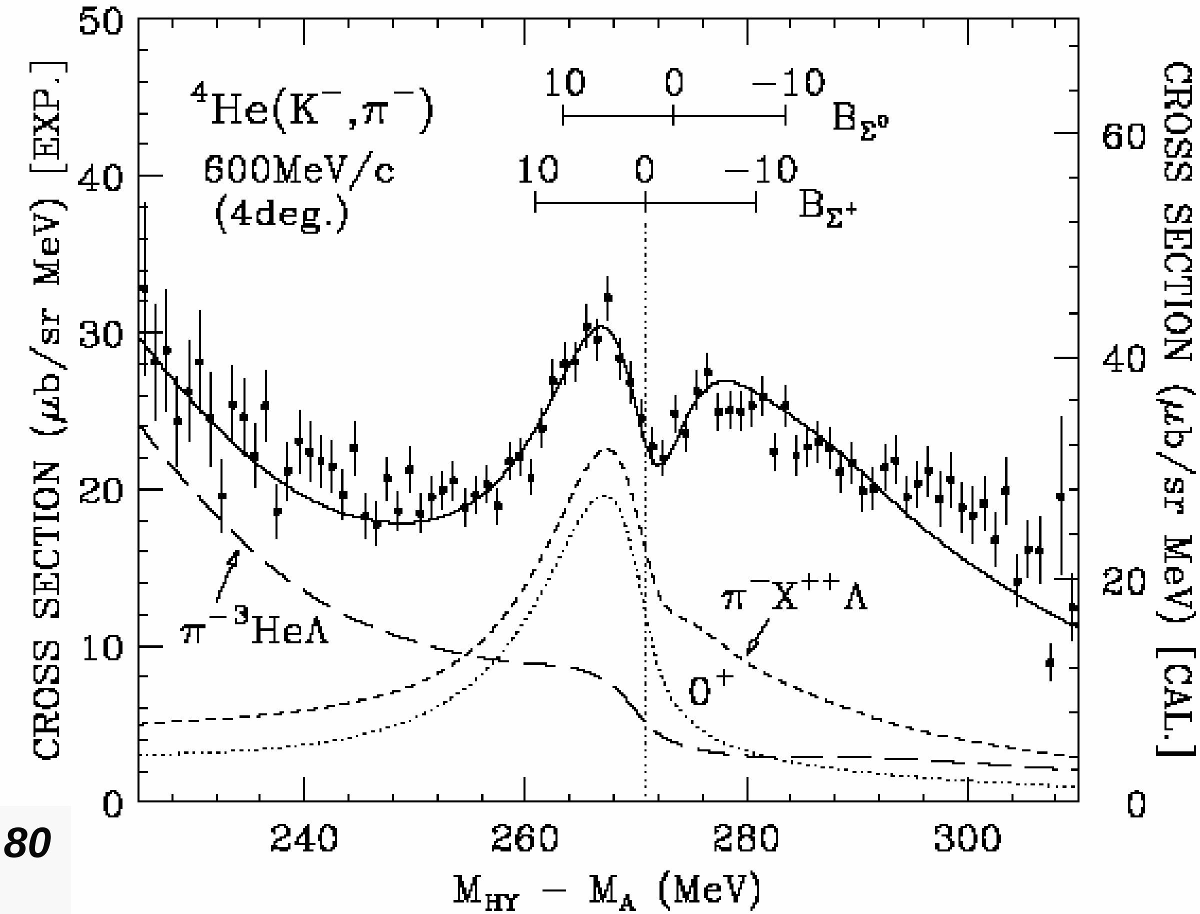


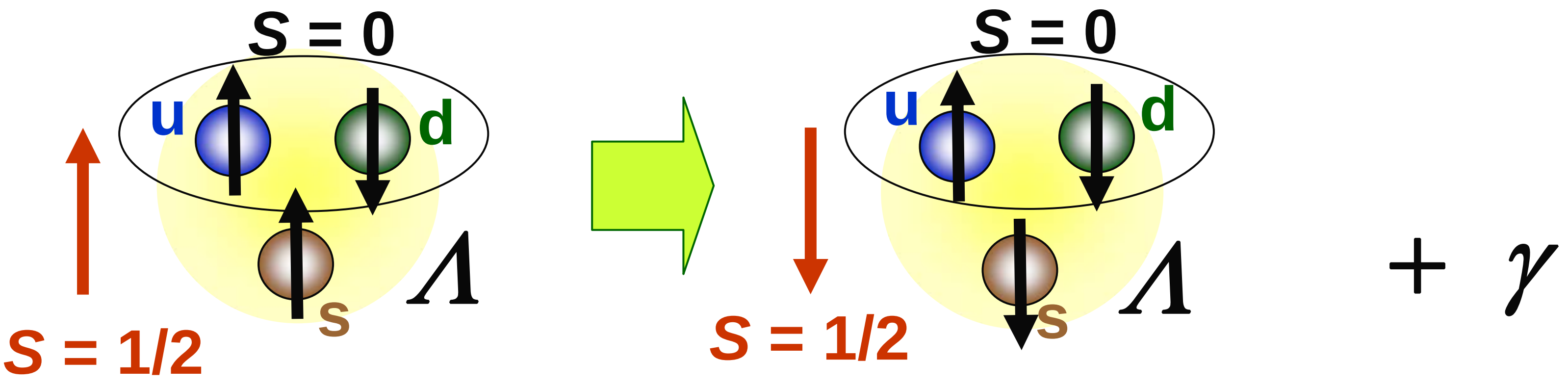
FIG. 3. Contributions to the ^{4}He(K^-, π^-) spectrum near the Σ threshold. The solid, long-dashed, and dashed curves are for the total π^-, π^- + ^{3}He + Λ, and π^- + X^{++} + Λ final states, respectively. The dotted curve denotes the contribution of $J^\pi = 0^+$ in the π^- + X^{++} + Λ final state.

calc: Harada, PRL 81(1998) 5287

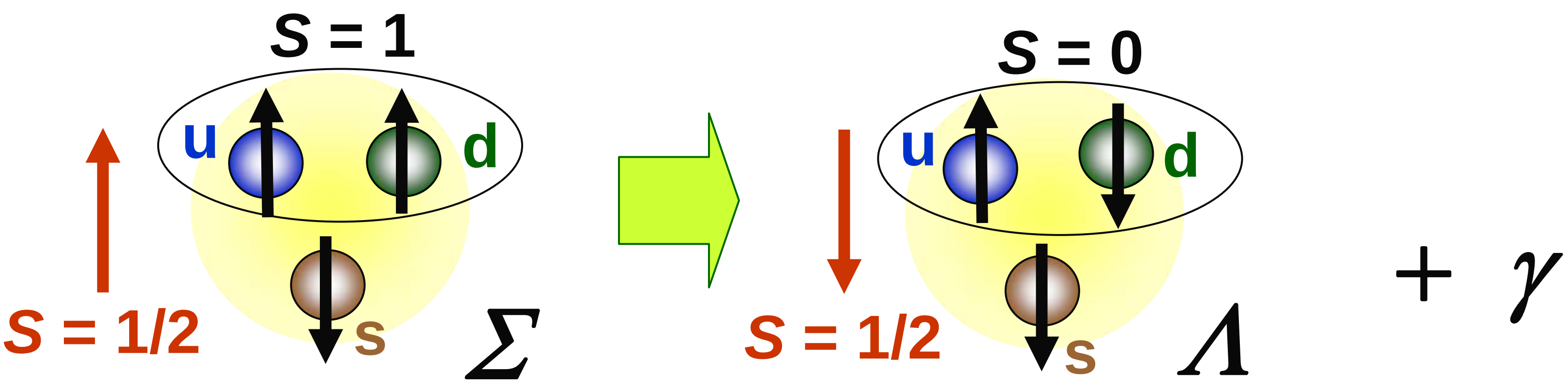
3. γ decay of Σ hypernuclei at K1.1

Spin-flip M1 transitions

$\Gamma \propto B(M1) \propto |\langle \downarrow | \mu | \uparrow \rangle|^2$ is sensitive to w.f.



Spin-flip of s quark – small medium effect ?



Spin-flip of u/d quarks – large medium effect ?

How large is the effect?

- Shift of constituent quark mass in a nucleus
  $\Delta m_{u,d}$ ~ -20%, $\Delta m_s / m_s$ ~ -4%

-> $\Delta\mu(\Sigma)$ ~ 20%, $\Delta\mu(\Lambda)$ ~ 4%
ΔB(M1) for Σ ~ +40%, ΔB(M1) for Λ ~ +8%

- Quark Cluster Model Takeuchi et al., N.P. A481(1988) 639

$\delta\mu/\mu$: ${}^{4}_{\Lambda}$He(1^+) -1% ~ -2%, larger by Σ mixing

${}^{4}_{\Sigma^+}$Li(1^+) -40% ~ -100%

b = 0.6 fm -> 0.8 fm, μ becomes twice large.

Measurement of $\Gamma(\Sigma^0 \to \Lambda\gamma)$ in a nucleus

Σ in nucleus = Σ hypernuclear bound states -> ${}^4_\Sigma$He

Free $\Sigma^0 \to \Lambda\gamma$ 100%, Eγ = 74 MeV
$\Gamma_{\text{free } \Sigma\to\Lambda\gamma} = 1 / 7.4\times10^{-20}\ \text{sec}^{-1} \sim 9\times10^{-3}$ MeV
$\Gamma_{\Sigma N\to\Lambda N} \sim 10$ MeV for ${}^4_\Sigma$He
=> BR($\Sigma^0 \to \Lambda\gamma$ in nucleus) ~ $\Gamma_{\Sigma\to\Lambda\gamma} / \Gamma_{\Sigma N\to\Lambda N} \sim 0.001$

(K^-,π^-) reaction at 600 MeV/c using K1.1BR
$d\sigma/d\Omega$ (${}^4_\Sigma$He) ~ 100 μb/sr (Nagae et al.)

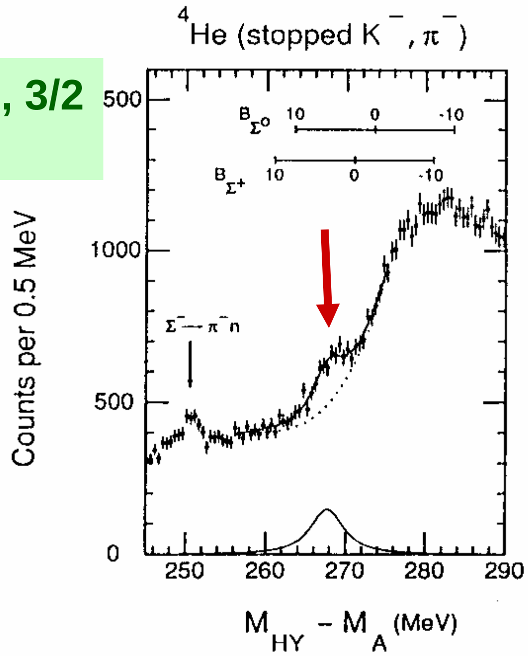
Yield: $N_{K^-} \cdot d\sigma/d\Omega \cdot \Delta\Omega \cdot BR \cdot N_{target} \cdot BR(\Lambda\to n\pi^0) \cdot \varepsilon$
$= 5\times10^5$ /spill $\cdot\, 100\times10^{-30} \cdot 0.02 \cdot 0.001 \cdot 0.12$g/cm^3/ $4 \cdot 20$cm $\cdot\, 6\times10^{23} \cdot 0.3 \cdot 0.5$
=> 56 counts/1000hour

Background: QF Σ^0 escape, $\Sigma^0 \to \Lambda\gamma$ ($-B_\Sigma > 0$ only)
$\pi^0 \to \gamma\gamma$ from $\Lambda \to n\,\pi^0$ (Eγ ~ 50~100 MeV)
=> Tag <u>3 energetic (> 50 MeV) γ rays</u>
=> cover the target region with a calorimeter

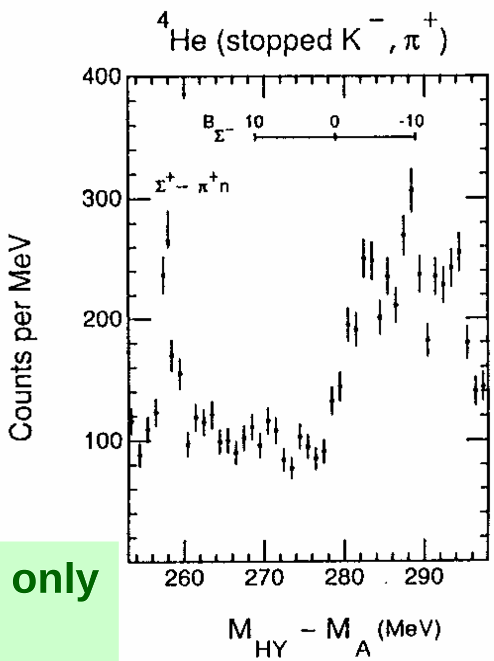
Theoretical calculation necessary – how large change is expected?

$^4_\Sigma$He by (K$^-$,π)

T=1/2, 3/2
S=0

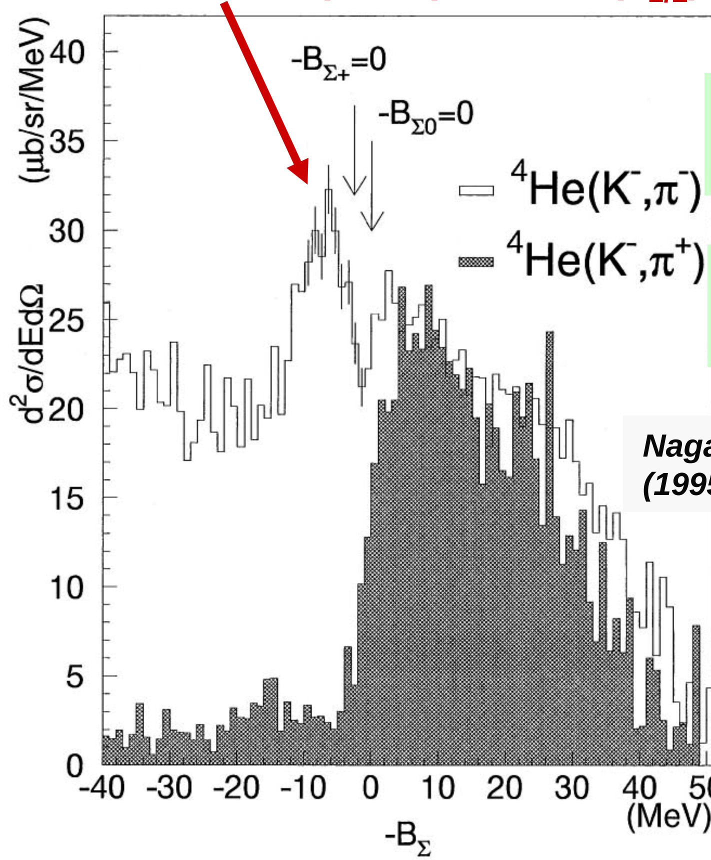


T=3/2 only
S=0



Hayano et al., PLB B231 (1989) 355

Substitutional ($\Delta L=0$) state: $n(s_{1/2})^{-1}\Lambda(s_{1/2}1)$



T=1/2, 3/2
S=0

T=3/2 only
S=0

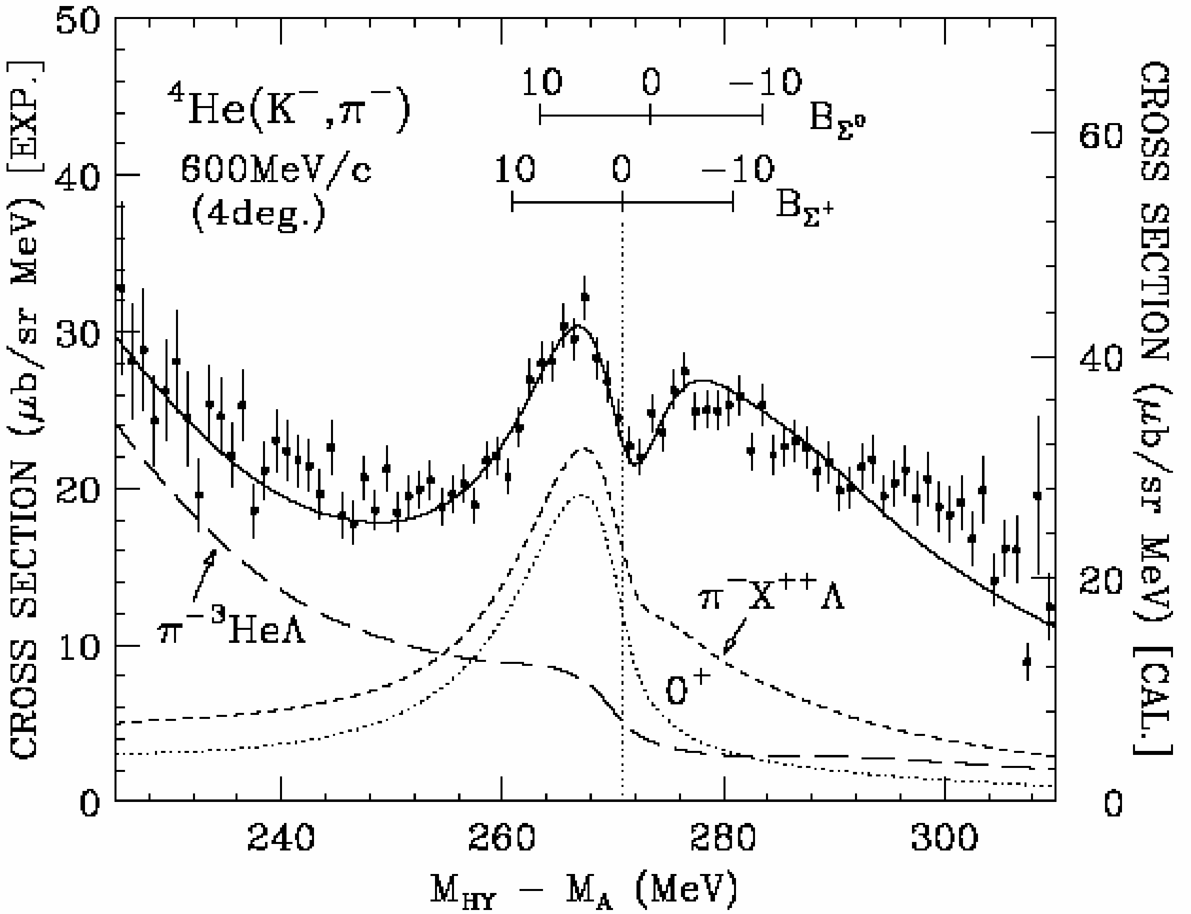
Nagae et al., PRL 80 (1995) 1605

Large spin-isospin dependence (Lane term)

- Consistent with ΣN interaction in Nijmegen D model
  - (I,S) = (3/2,0), (1/2,1) attractive, (3/2,1), (1/2,0) repulsive

No peaks in other Σ hypernuclei

- Width ($\Sigma N \rightarrow \Lambda N$) > 10 MeV in general-- spectroscopy difficult



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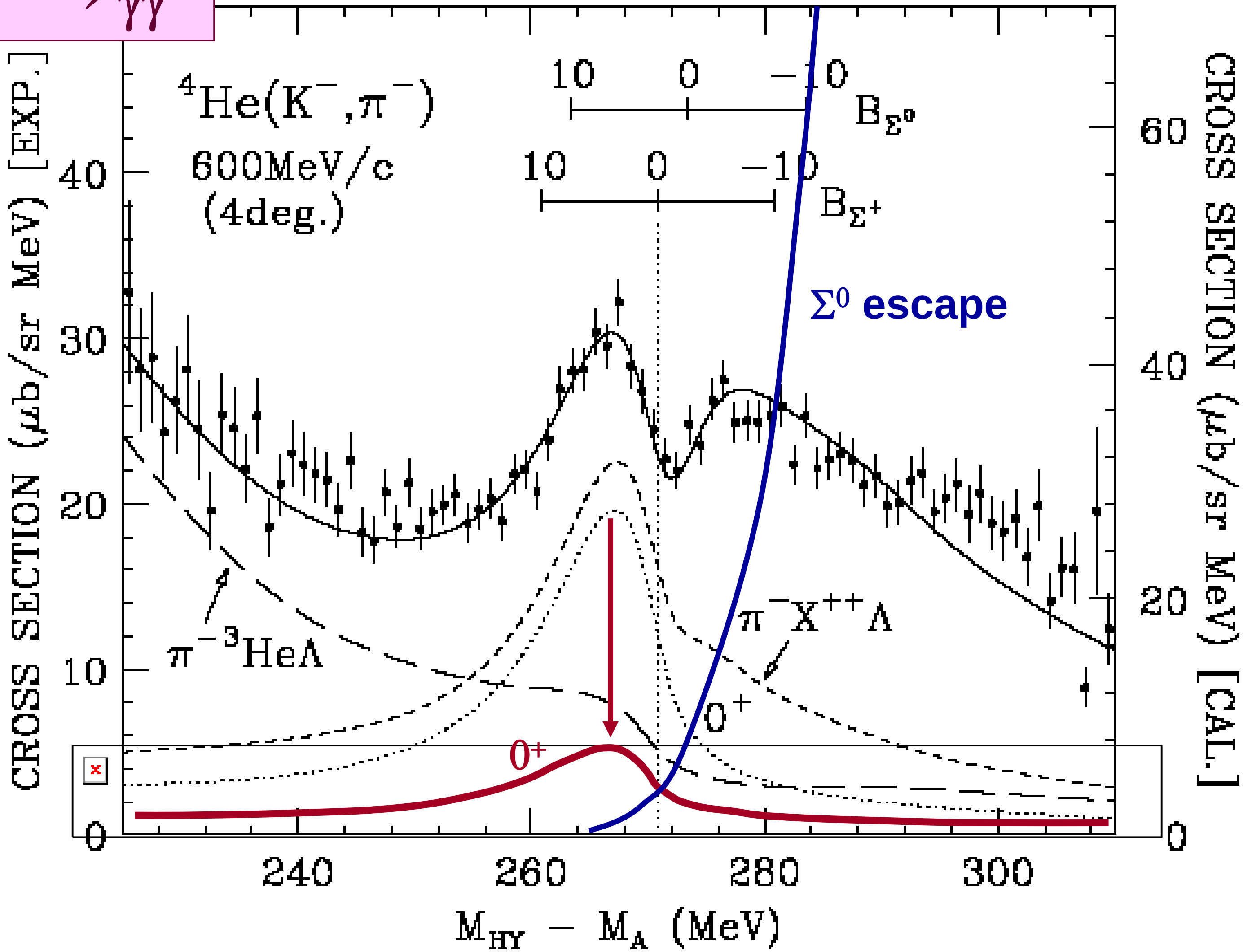
Harada, PRL 81(1998) 5287

Expected 3γ-tagged spectrum (イメージ)

$\Sigma^0 \rightarrow \Lambda\ \gamma$
$\rightarrow n\pi^0$
$\rightarrow \gamma\gamma$

Assuming that ^{3}HeΛ, pdΛ, ppnΛ never emit 3 energetic γ's



Summary

- γ-ray spectroscopy of Λ hypernuclei at K1.1
  - Various experiments using SKS + Hyperball-J
- Σ hypernuclei at K1.1BR
  - ^{3}He(K-,π) for ΣN spin-isospin dependence
  - γ decay of Σ hypernuclear bound states

- New apparatus to be build

2nd SKS (or "SKS2" at K1.8)

Beam spectrometer for K1.1BR

π^0 spectrometer

Calorimeter (crystal barrel)